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HYBRID POWER SOURCE FOR VEHICULAR PROPULSION.(U)
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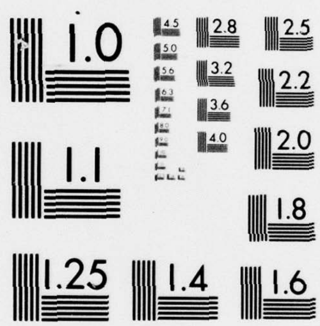

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BACKGROUND

The only current off-the-shelf contender for powering electric vehicles, the lead acid battery, needs help! Gasoline contains about 5000 watt-hours of energy per pound (11 KWH/kg) while its lead acid "challenger" produces about 11 watt-hours per pound (24 WH/kg) in powering a typical electric vehicle. This paper presents a means of overcoming this energy disparity - a hybrid lead acid battery-fuel cell power source.

The Army has a requirement for higher energy density power sources for electric vehicles, the most immediate of which is for material handling equipment (MHE) such as fork lift trucks. Future military needs are anticipated in utility trucks and pick ups or vans. The two main paths being explored are higher energy density molten salt batteries, 82 WH/lb (180 WH/kg), and hybrid, or load sharing power sources. The hybrid fuel cell-battery power source technology is a prime candidate for providing a viable electric vehicle power source. Compared to present battery and engine technology, the hybrid technology should increase range, improve performance, reduce air pollution, increase efficiency and expand the options available to meet requirements in cost, size and weight. The need for improvements is particularly evident during emergencies such as the Vietnam War, when increased ammunition movement from narrow door storage igloos, up ramps to trucks was seriously hampered by the poor performance, range and large volume of present batteries in electric fork lift trucks.

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INTRODUCTION

Hybrid power sources are composed of two separate power sources, capable of operating at the same time into a common load. They typically use a high specific energy (WH/kg) source such as an engine or fuel cell coupled with a high specific power (W/kg) and storage source such as a battery or flywheel. A battery-flywheel hybrid is currently under development by Garrett Air Research (1). In this case, the battery is the energy source.

The underlying purpose of the hybrid approach has been to allow operation of the major energy source near optimum design by supplying only the base or average load requirements. The storage source then supplies the transient load increases and is recharged when the load drops below average. Thus, the load variation experienced by the energy source is reduced in frequency and magnitude. This allows for design and operation within a band representing the average, rather than design for peak with dominant operation under off-peak conditions. Reduced emissions and increased efficiency are expected benefits from operation of hybrid systems.

This paper will present the design and performance characteristics of a hybrid, fuel cell-battery power source for use in MHE and other military electric vehicles.

HYBRID POWER SOURCE

The hybrid, fuel cell-battery power source is shown in Figure 1.

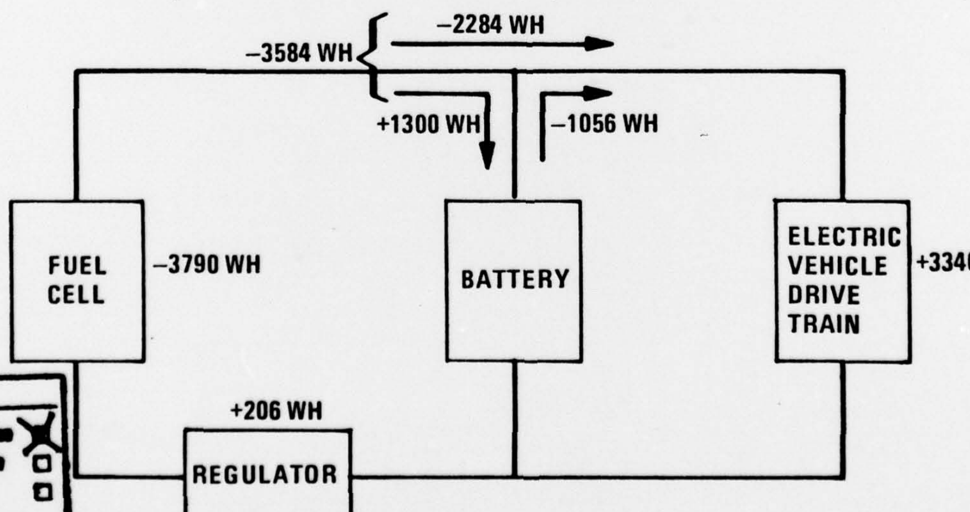

Figure 1 FUEL CELL/BATTERY HYBRID POWER SOURCE

Figure 1 shows a fuel cell energy source with a series regulator for limiting the voltage from the fuel cell to charge the battery and for limiting the current out of the fuel cell to a value that will maximize fuel cell life. The fuel cell and battery supply power to the load, in this case, an electric vehicle drive train consisting of a controller and a differential-motor drive. The interplay between the fuel cell and battery is illustrated in Figure 2. The system terminal voltage common to the load and battery is represented by the thick line in the case of a charged battery and the thick dashed line in the case of a discharged battery. The fuel cell load line extends from OCV_{FC} (the open circuit fuel cell voltage) to the relative current abscissa. The battery discharge follows a load line starting between OCV_{B1} or OCV_{B2} depending on the state of charge of the battery. The regulator can be preset to limit the maximum battery charge voltage to MAX V_B, the battery is charged by the fuel cell; some fuel cell current goes to the battery and some to the load depending on the relative currents at the same voltage. Charging occurs in the stripped regions. When the battery drops below minimum voltage, MIN V_B, motor current becomes excessive. A continuation of this will eventually cause the motor thermal cut out to be activated. The fuel cell current is held at 1 I_{FC} by the regulator. The regulator's power dissipation is the product of its voltage drop, V, and 1 I_{FC}.

The fuel source in lift truck feasibility studies was cylinders of compressed hydrogen gas. A methanol steam reformer is under development at MERADCOM to supply the hydrogen in the future. The fuel cell power source consisted of four, one kilowatt, stacks that were connected electrically in parallel. The stacks were fabricated by increasing the number of cells in existing 750 watt stack technology, built by Engelhard Industries. These stacks are based on phosphoric acid technology and utilize hydrogen and air. Each stack has its own blower for air and temperature control and is supplied fuel from a common hydrogen manifold. Each stack is rated to produce one kilowatt at 42 volts. The battery consisted of six auto ignition batteries. Two groups of three series connected 12 volt batteries were connected in parallel. The ignition batteries were chosen because of their low internal resistance and high rate capability. The regulator was a modified transistorized load bank. It consisted of 66 transistors connected in parallel which are capable of dissipating 1000 watts at currents up to 110 amperes.

LOAD PROFILE ACQUISITION

To design a hybrid power source, data on the temporal frequency distribution of the load is necessary (2). Information on the power required during travel and lifting with various loads was available but the frequency, duration and magnitude of these events had not been adequately recorded. Thus, the initial phase of designing a lift truck power source required a determination of these parameters for a conventional, battery powered truck.

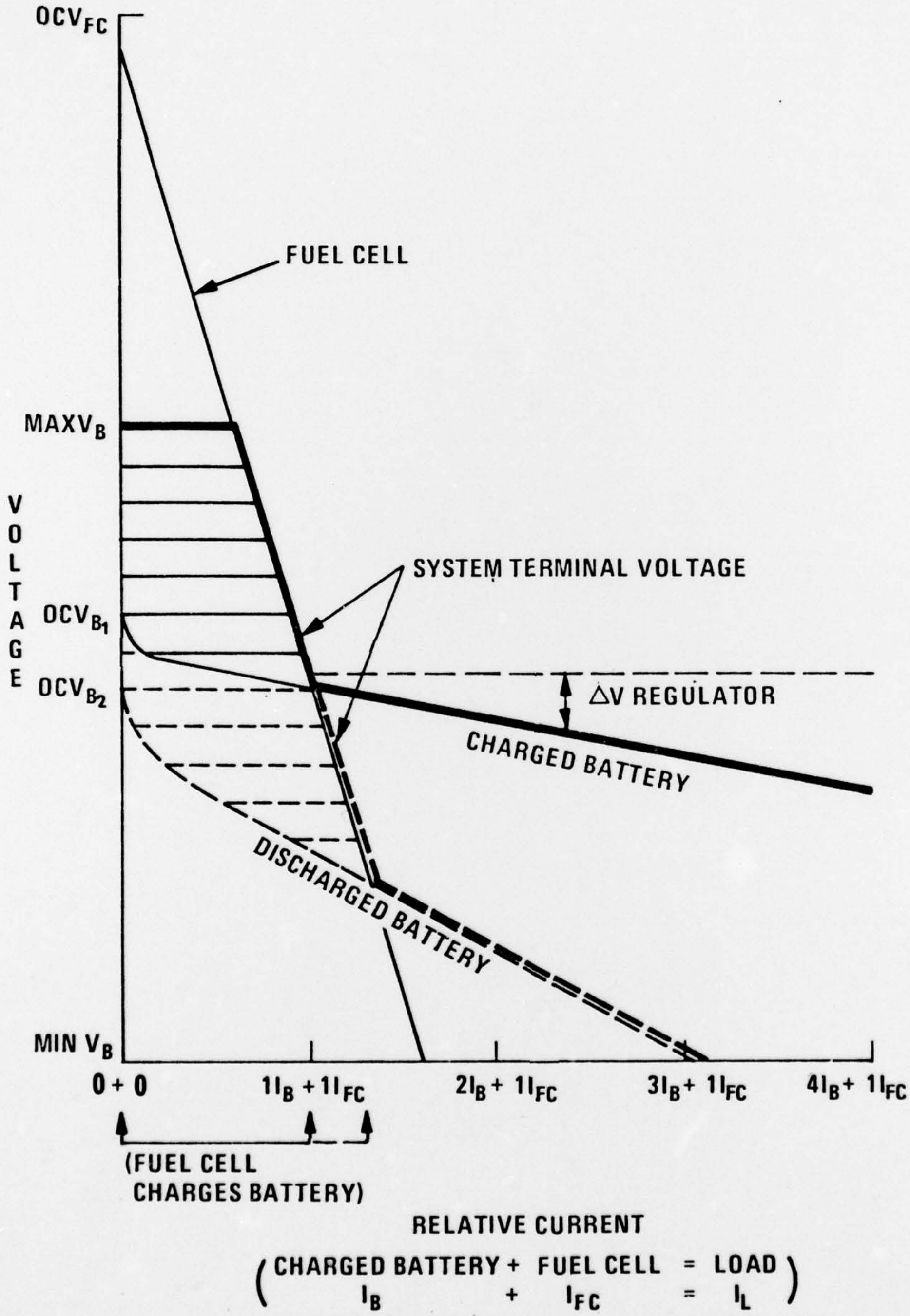

Figure 2 HYBRID CHARACTERISTICS

Instrumentation consisted of signal conditioning circuits and a magnetic tape recorder for recording analog signals of electrical parameters. The tape recorder was operated at 1.875 inches (4.763 cm) per second. The signal conditioning circuitry consisted of a main battery voltage divider, a shunt-voltage amplifier for current monitor, an analog multiplier and circuits for averaging power and current to increase the effective frequency response of the recorder. The parameters measured were battery voltage, current and power and vehicle velocity. Current and power were recorded both raw and electronically averaged. The raw recorded values preserved the rapid switching transients associated with the solid state controller. This instrumentation package was mounted on an electric vehicle during field operation.

The field recorded analog signals were then reproduced and prepared for analysis by conversion to a digital format with a high speed 15 bit A/D converter. From this data, frequency of occurrence distributions for velocity, current and power were derived. This was accomplished by counting how often preset incremental values of these parameters were exceeded.

Programs are available for estimating hybrid behavior using the data and a simple model. The model assumes that the average power is available from some primary (energy) source. When the measured demand exceeds this level it is supplied by a storage device. Conversely when the demand drops below that available the surplus is returned to the storage device. Allowance was made in the programs for some variation in transfer efficiencies in charge and discharge of the storage device. The size of the device is based on the maximum and minimum energy levels determined during processing of the profile data.

LOAD PROFILE ANALYSIS

The results of analysis of field data will be presented for a 4000 pound capacity fork lift truck that was instrumented as described above and operated over the Military Standard Endurance test course (3). This test course is a cyclic route involving three load placements and a ramp. Since load placement is done on one lap and removal is performed on another, it required two laps of the route to yield one cycle. A segment of the strip chart, Figure 3, displays the analog current and velocity from this profile and the identifiable events. The frequency of occurrence distribution for power is shown in Figure 4. The negative power values result from the minor noise about zero and some transients due to tape head vibration. These have subsequently been reduced to insignificance with new Hall effect devices and improved recorder design and mountings. This distribution shows clearly the relationship between peak to average power demand. The average power demand was determined by computer integration of the power levels.

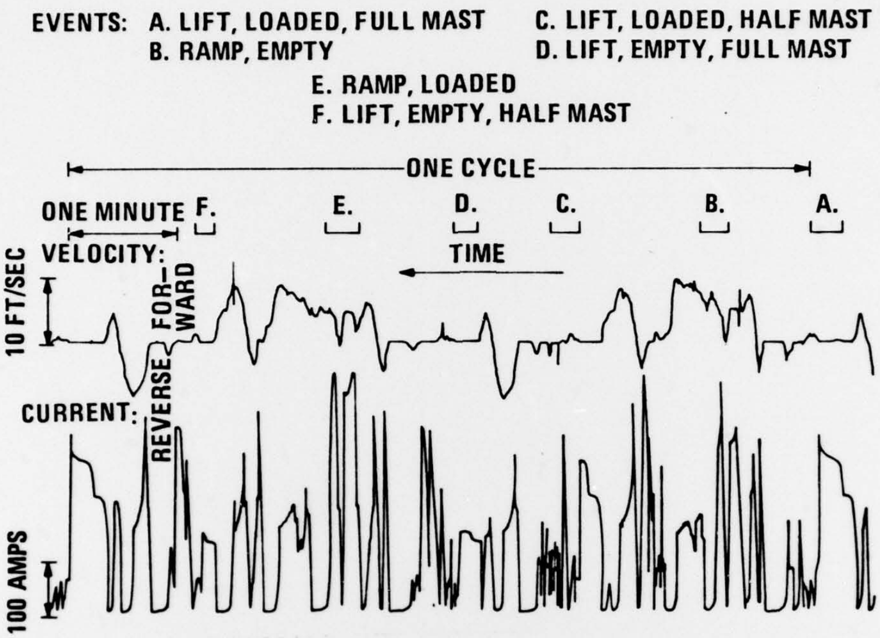

Figure 3 CURRENT-VELOCITY PROFILE FOR MIL. STD. TEST COURSE

The cyclic MIL. STD. route, wherein the same tasks are performed regularly, results in a distribution with local maxima. The full capacity lifts consumed considerable time and energy. The stopped/no work mode is an integral part of the work cycle. No work breaks are included. The data can yield the distance and travel time for discrete periods of motion. An analysis is shown in Figure 5 where the percent-of-total values indicate the percent of the total travel time represented by an interval.

The last seven entries of Table 1 represent characteristics of the hybrid derived from the computer simulation. The time spent in charging the energy storage device was roughly equal to that in discharge. Of particular importance is the energy transfered through the storage device. Forty-four percent of the energy used while performing the task came from, i.e. passed through, the storage device. Because the magnitude of the pulses, discharge and charge are small, the theoretical storage required is quite small, 0.18 Kwh. The small theoretical size indicated and the large fraction transfered implies high transfer rates are required. A term to express this is the capacity cycles per hour; this represents the number of times energy, equivalent to the capacity, is cycled through both discharge and charge. Cycles in the normal sense have no real meaning relative to a hybrid since the device may be fully discharged only once during many capacity cycles.

The above value of storage required was based on a model that assumed 100% transfer efficiency. This is not realistic. The next section describes laboratory operation with a fuel cell, batteries and regulator responding to field recorded load profiles.

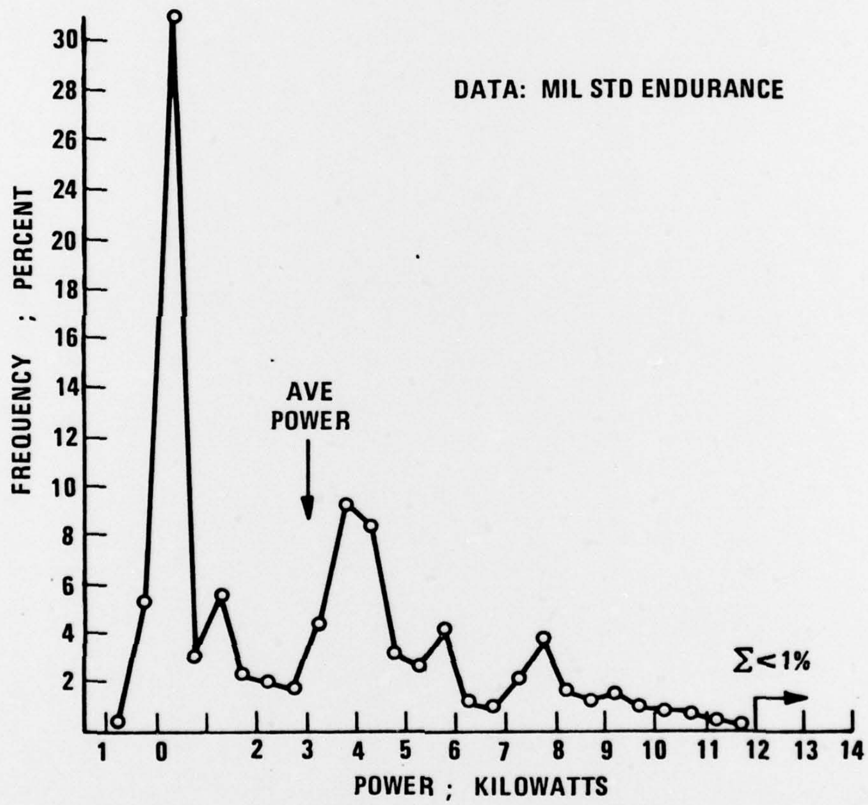

Figure 4

FREQUENCY-OF-OCCURENCE DISTRIBUTION FOR VELOCITY

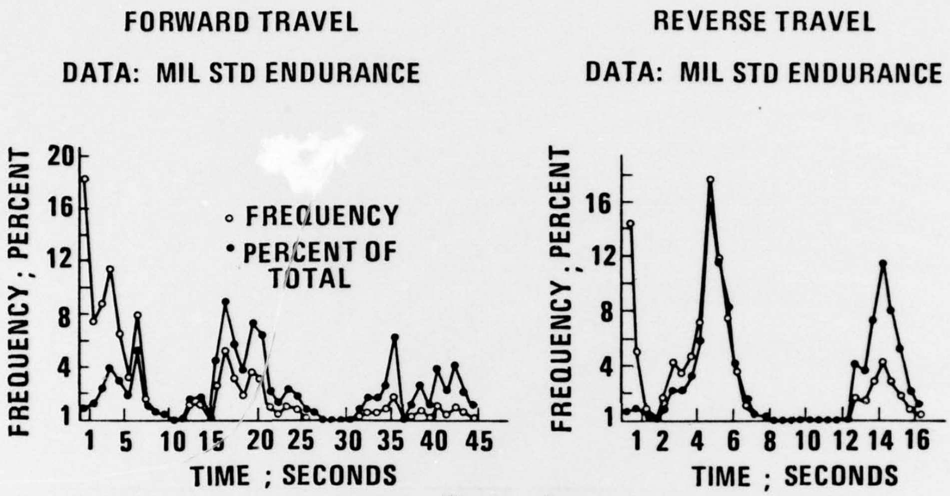

Figure 5
DISTRIBUTIONS FOR TRAVEL PERIODS, TIME, FREQUENCY AND PERCENT-OF-TOTAL

Table 1
SUMMARY OF ANALYSIS OF MILITARY STANDARD ELECTRIC FORK LIFT TRUCK PROFILE

Duration Min.	147.
Average Power, Watts	3040.
Kilowatt-Hr/Mile	1.54
Forward:	
% Time	46.
% Energy	46.
Reverse:	
% Time	17.
% Energy	16.
Stopped/Lift	
% Time	24.
% Energy	38.
Stopped/No Work	
% Time	14.
Charge, % Time	51.
Avg. Power	2580.
Discharge, % Time	49.
Avg. Power	2710.
Energy, % Transferred	44.
Storage Size, KWH	0.18
Capacity Cycles/Hr.	7.4

LABORATORY TESTING WITH FIELD PROFILES

The following field profiles for testing a hybrid were recorded by instrumenting a 4000 pound capacity electric fork lift truck at the Red River Army Depot, Texarkana, Texas. RRD #5 - An electric fork lift truck replaced a gasoline lift truck in the shipping department where a variety of items were picked up and loaded into trucks; RRD #4 - Ammunition was unloaded from a train freight car to a truck, and then removed from the truck, taken down a ramp, and placed in a storage igloo; RRD #3 - Ammunition was removed from an igloo, taken up a long ramp to a truck and the fork lift truck returned, empty, for more ammunition.

The data in Table 2 was acquired by operating with the previously described fuel cell-battery hybrid power source including the regulator against these field profiles. The discharge profiles were controlled in the laboratory by a unique in-house simulator (4). This simulator is ideal for hybrid studies. It can change from a charge to a discharge current of 1000 amperes in 0.2 seconds. To generate the data in Table 2, it was programmed by the field recorded magnetic tape profiles set to reproduce the actual field current levels.

The energies from Table 2 for the RRD #5 profile are shown in Figure 1, next to their associated components for clarity. Adsorbed energy is positive and removed energy is negative. The +1300 WH represents energy into the battery. The energy actually accepted by the battery was not measured. Future tests are planned to measure this as well as the effects on the battery life.

The profiles in Table 2 are presented in the order of increasing current and power. The MIL. STD. profile is included in the table for comparison. The MIL. STD. and RRD #3 profiles have a significant net battery capacity loss. Both profiles represent an unusual use of a fork lift truck. The endurance run is designed as a test of the mechanical components of the truck not the power source. It exceeds all field requirements. No coffee or lunch breaks are included in the profile. These non-drain periods would allow fuel cell recharge of the battery. The RRD #3 ammunition run is mainly used during war emergencies. The RRD #3 operation only lasted about one hour when the truck's motor overheated. The battery voltage had decreased rapidly under the high power ramping conditions. This required increasing currents to maintain the required power. Since generated heat is directly proportional to the square of the current, the motor overheated.

Adding one 1 KW fuel cell module should significantly extend the duration of the MIL. STD. and the RRD #3 profiles. The ramping operation in the RRD #3 profile should not increase in duration due to the stiffer system voltage. the time saved could be used for recharge by the fuel cell. The increased system voltage should prevent the motor over-

heat experienced while determining the field profile and thus operation time should be dependent on the quantity of fuel.

TABLE 2

LABORATORY PERFORMANCE OF HYBRID POWER SOURCE WITH FIELD LOAD PROFILES

Profile	RRD #5	RRD #4	MIL. STD.	RRD #3
Test Time, Hours	2.0	1.4	2.6	1.2
System Load:				
Avg. Current, Amperes	44	80	97	134
Avg. Power, Watts	1670	3030	3435	4710
Energy, Watt Hours	3340	4242	8931	5652
Fuel Cell Subsystem:				
Avg. Current, Amperes	48	83	94	94
Avg. Power, Watts	1895	3240	3490	3420
Energy, Watt-Hours	3790	4536	9074	4104
Regulator Loss, %	5.4	4.9	3.5	4.1
Battery Subsystem:				
Charge				
% Time	76	61	55	42
Avg. Current, Amperes	20	37	70	42
Avg. Power, Watts	855	1515	2745	1630
Energy, Watt-Hours	1300	1294	3925	822
Discharge				
% Time	24	39	45	57
Avg. Current, Amperes	60	62	101	108
Avg. Power, Watts	2200	1223	4101	2538
Energy, Watt-Hours	1056	1223	4101	2538
Net Change, Amp.-Hours	+2.0	-1.4	-20.5	-52.3
Net Change, Watt-Hours	+244	-71	-176	-1716

HYBRID-FUEL CELL OPERATIONAL EXPERIENCE

The hybrid power source was operated in a 4000 pound capacity fork lift truck for three years. During this period the fuel cell experienced about 54 thermal (on-off) cycles and accumulated over 250 hours of operation. The only discernable change has been a slight increase in operating temperature. This temperature normally ranges between 200 and 210°F. The system sealing seemed to be holding well. Hydrogen cross leaks were not detectable and there was no indication of acid leaks.

FUTURE MILITARY APPLICATIONS

Extending the range and performance of electric fork lift trucks with a hybrid power source would make it possible to replace not only current electric trucks but make significant inroads on gasoline powered trucks. Twenty-eight battery-powered cargo carriers of a 2-passenger, 4-wheel type with a flat cargo bed have been purchased for a facilities engineering work force at the Military District of Washington. The low maximum speeds of 10-12 mph and the lack of power to negotiate hills could be overcome with a hybrid power source, with increased range.

Several military truck manufacturers have indicated that they would respond to a documented army requirement for electrics. An assessment of present and future military use of electric vehicles is needed. A preliminary study was published in 1976 (5). The potential for replacing gasoline powered vehicles with electrics was determined for three military bases: McClellan Air Force Base, Fort Ord Army Base and the Long Beach Naval Shipyard. The results are summarized in Table 3. The study was based on lead acid electrics. Hybrid electrics' enhanced performance should assure rapid replacement of such conventional vehicles.

MERADCOM, under an interagency agreement with the Department of Energy, is conducting state-of-the-art assessments of electric and hybrid vehicles. A representative electric passenger vehicle, with a gross weight under 4000 pounds (1814 KG), has performance requirements that could be met by a hybrid power source up to about 35 mph as shown in Table 4. The peak to average power ratios are similar to that of the fork lift truck, namely 4 or 5 to 1. Cruise peak power was not given since this peak only occurs one time during the initial acceleration and is below the schedule B and C powers. For example, the 48 mph acceleration peak power is about 22 KW.

TABLE 3

EXAMPLES OF CONVENTIONAL MILITARY VEHICLES
POTENTIALLY REPLACEABLE BY ELECTRICS

Vehicle Type	Number of Vehicles in Class	Potentially Replaceable by Electrics*	Average Daily Mileage	Vehicle Application and Comments
1/2 Ton Pick-Up	390	197	44	Onbase Maintenance and Repairs, some personnel Transportation and Messenger Service.
3/4 Ton Utility Truck	155	75	22	Onbase Maintenance and Repairs.
29 Passenger Bus	17	11	49	Onbase Bus Service
1 Ton Metrovan	40	40	22	Used for Mail Distribution, Aircraft Maintenance, and delivery of Flight Crews on Base.
3 Wheel, Low Speed Truck	41	41	13	Onbase Messenger and Light Repair Service.

*Criteria: Maximum daily use would be 40 miles and top speed requirement would be 25 miles per hour.

TABLE 4

POWER REQUIRED BY A TYPICAL ELECTRIC PASSENGER VEHICLE

Mode of Operation	Peak Power (KW)	Average Power (KW)	Ratio PK/Avg.	Duration (Hours)
SAE-J227a				
Schedule B	26	5.3	5	1.7
Schedule C	30	7.6	4	1.2
CRUISE				
25 MPH	--	7.9	--	1.5
35 MPH	--	12.0	--	0.8
48 MPH	--	16.6	--	0.5

CONCLUSIONS

An Army assessment of electric vehicle applications should be conducted. Inclusion of hybrid fuel cell-battery power sources in the assessment is expected to provide the margin required for successful resolution of present lead acid battery deficiencies. This may accelerate the development of electric vehicles as a practical alternative to conventional gasoline vehicles.

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